Numerical Weather Prediction

Measurement Noise and Stratospheric Gravity Wave Characteristics obtained from GPS Occultation Data

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Abstract

Tsuda and Hocke (2002) reduce the amount of filtering applied to raw radio occultation data in order to increase the vertical resolution of GPS based temperature retrivals in the stratosphere. The authors discuss gravity wave characteristics obtained from these optimised retrievals, including characteristics of vertical wave number spectra for vertical wavelengths below 2 km, and the meridional distribution of potential energies for such short wavelengths.

The filtering of raw data is required because real measurements contain noise. In this note, we discuss the role of measurement noise for gravity wave characteristics obtained from dry temperature retrievals of GPS based radio occultation soundings. We show that for realistic noise levels, temperature fluctuations can be safely interpreted as originating from small scale atmospheric waves in the altitude region below 30 km and for wavelengths above 2 km, with the detailed limits depending on noise and retrieval characteristics. An optimising procedure as the one applied by Tsuda and Hocke, however, may raise noise related effects to the level of atmospheric waves for short vertical wavelengths. We further show that conclusions for vertical wavelengths below 2 km, if at all, can only drawn after taking the actual noise characteristics of the observations and the details of the filter procedures applied in the retrieval into account.

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1 Introduction

By “optimising” an otherwise standard dry temperature retrieval of GPS/MET radio occultation soundings, Tsuda and Hocke (2002, hereafter TH02) claim to retrieve lower and mid stratospheric temperature fluctuations related to gravity wave activity on small vertical wavelengths down to 400 m between 20 and 40 km altitude. Their work is in response to an earlier finding by Steiner and Kirchengast (2000), who noted that previously published GPS/MET profiles (e.g., by Rocken et al., 1997) underestimate the spectral density of lower stratospheric temperature fluctuations for vertical wavelengths below 2 km. According to Steiner and Kirchengast, the underestimation of gravity wave activity at these wavelengths is due to filtering of raw excess phase delay data. The work by TH02 can be understood as a heuristic approach to improve the estimation of gravity wave characteristics from radio occultation data by tuning retrieval parameters: The higher vertical resolution obtained by TH02 is achieved by reducing the width of the excess phase filter (their parameter N_{ASOFF}). TH02 tune this parameter in order to obtain vertical gravity wave number spectra between 20 and 30 km altitude in the tropics which are consistent with the spectral shape expected from gravity wave saturation theory for small vertical wave lengths. The authors then discuss the latitudinal variation of gravity wave spectra with special emphasis on short vertical wavelengths below 2 km, and for altitude ranges of 20–30 km and 30–40 km, respectively.

The retrieval algorithm used in TH02 is based on excess phase data calculated from the raw GPS signal (Hocke, 1997). More advanced retrieval methodologies like Back Propagation (Gorbunov and Gurvich, 1998), Radio Holography (Hocke et al., 1999), Canonical Transform (Gorbunov, 2001, 2002) or Full Spectral Inversion (Jensen et al., 2003), which also employ amplitude data, are not applied. Thus, a lower physical limit of the vertical resolution of radio occultation data is given by the size of the Fresnel diameter (Hinson and Magalhaes, 1991; Melbourne et al., 1994; Kursinski et al., 1997). The Fresnel diameter depends on the radio signal’s wavelength (in the order of 20 cm for GPS signals) as well as on the distance of the receiver from the tangent point of the observation.

For GPS/MET, the Fresnel diameter is in the order of 1.4 km in the mid stratosphere and above, decreasing to about 800 m at tropopause altitudes (Rocken et al., 1997; Hajj et al., 2002). Strictly speaking, the 400 m resolution claimed to be achieved by TH02 is beyond the physical capabilities of GPS radio occultation measurements, at least with the retrieval algorithm used in their study.

Filtering of raw excess phase delay data is required because the measured signal contains noise (Rocken et al., 1997; Hajj et al., 2002). This originates from thermal receiver noise, but may also contain ionospheric effects present in both the occultation and a reference link to a second satellite of the GPS constellation (data from a reference link is used for double differencing, which aims at correcting for clock errors). In case of GPS/MET, the thermal noise of the double differenced phase delays has been estimated to exhibit a standard deviation in the order of 1 mm for the L1 frequency, and slighty more for the L2 frequency (e.g., Kursinski et al., 1997; Hajj et al., 2002). Because the nominal resolution of the retrievals used in TH02 is smaller than the Fresnel diameter, it cannot be excluded that part or all of the conclusions drawn by TH02 on gravity wave characteristics for vertical wavelengths below 2 km are related to sub–Fresnel scale noise, rather than to atmospheric gravity waves.

A correction of ionospheric effects, usually undertaken for bending angles, further adds to the noise level of radio occultation data (Vorob'ev and Krasil'nikova, 1994); firstly because of the necessary interpolation of an already noisy bending angle obtained from L2, and secondly because higher order ionospheric effects are not properly corrected for. Therefore, a second smoothing (or filtering) step is usually applied in standard radio occultation retrievals, often referred to as "statistical optimisation" (Sokolovskiy and Hunt, 1996; Hocke, 1997; Healy, 2001b). Depending on the details of the implementation, small vertical scale features of retrieved temperature profiles may either be retained, as in Sokolovskiy and Hunt (1996) or Hocke (1997), or completely suppressed (as in Healy, 2001b). We note that the statistical optimisation includes the use of climatology data, which may cause systematic biases in the mid stratosphere (Marquardt et al., 2001, 2003).

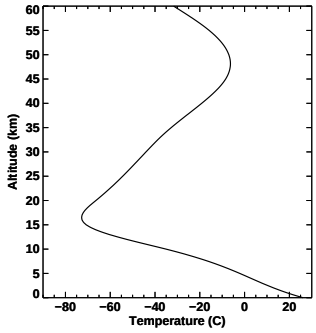

Fig. 1: The tropical temperature profile from the Cospar International Reference Atmosphere (CIRA; Barnett and Corney, 1985; Hedin, 1991) climatology used in the simulations.

Having these issues in mind, it may be asked for which vertical wavelengths and in which altitude regions dry temperature fluctuations as analysed in TH02 can indeed be interpreted as gravity wave signal, and to what degree they simply reflect noise. In this note, we study the effects of uncorrelated Gaussian random noise on gravity wave characteristics, and especially vertical wave number spectra, estimated from dry temperature retrievals. Section 2 presents the results of a Monte-Carlo simulation for noise levels typical for GPS/MET (and, as we will show, also CHAMP) data. We discuss some implications of our results for the work of TH02 in section 3. Because TH02 only varied a single parameter in the excess phase delay filtering, we will also restrict our discussion on the effects of varying this parameter. A detailed study of the effects of various implementations of the statistical optimisation is beyond the scope of this work.

2 Measurement noise and gravity wave characteristics

We use a tropical temperature profile (Fig. 1) from the CIRA climatology (Barnett and Corney, 1985; Hedin, 1991) to construct a spherically symmetric refractivity field. Excess phase delays for both L1 and L2 GPS frequencies were calculated using a geometrical optics ray tracer (Healy, 2001a) and sampled at the 50 Hz rate typical for present day GPS receivers like those used in the GPS/MET mission. The ionosphere is represented by an idealised Chapman–layer of electron densities with parameters describing an undisturbed ionosphere under low solar activity conditions (as prevailing during the GPS/MET

mission). No temperature fluctuations have been added to the original profile; we stress that the profile does not exhibit any small vertical scale wave related features.

For practical reasons, we based our ray tracing calculation on orbits of a tropical occultation taken by the German CHAMP satellite (e.g., Wickert et al., 2001; Marquardt et al., 2003) near Nairobi on 15 May, 2001. Because GPS/MET exhibits a higher orbit altitude ($\approx$ 750 km) than CHAMP ($\approx$ 430 km), we chose filter widths of 15, 27 and 41 data points to compare with the results obtained by TH02 (their parameter N_{ASOFF} was set to values of 10, 20 and 30). For typical downward progression rates of the tangential point for GPS/MET and CHAMP occultations, these settings represent similar filter widths in the vertical (rather than temporal) domain. Specifically, our 15 point filter corresponds to the 10 point optimised filter chosen by TH02, while the $n = 27$ filter is comparable to TH02's 20 point filter. The 41 point filter refers to TH02's baseline retrieval. For illustrative purposes, we have also applied a filter of 81 data points.

We added uncorrelated Gaussian noise to the simulated excess phase delays for both GPS frequencies, and performed dry temperature retrievals for different phase delay filter widths. Because the L2 frequency is expected to exhibit larger noise levels compared to the L1 signal (e.g., Hajj et al., 2002), the simulated excess phase delay noise on the L2 data has been increased by 20% with respect to L1. The retrieval implemented for this study consists of a 3rd order polynomial filter for the phase delays, followed by the usual calculation of bending angles from the phase delay's derivative with respect to time, and an ionospheric correction of the bending angles (Vorob'ev and Krasil'nikova, 1994). A statistical optimisation (as described in Hocke, 1997) is applied above 30 km, followed by an Abel transform to obtain refractivity as function of altitude. Dry temperatures are calculated by integrating the hydrostatic equation. Fig. 2 shows the difference between a dry temperature profile based on a randomly selected realisation of noise for different widths of the phase delay filter and the mean temperature retrieval obtained from a 1000 member Monte Carlo ensemble. The figures show that temperature fluctuations related to noise exhibit wave-like behaviour, where the vertical wavelength is determined by the filter width. We note that even in the case of excessive filtering over

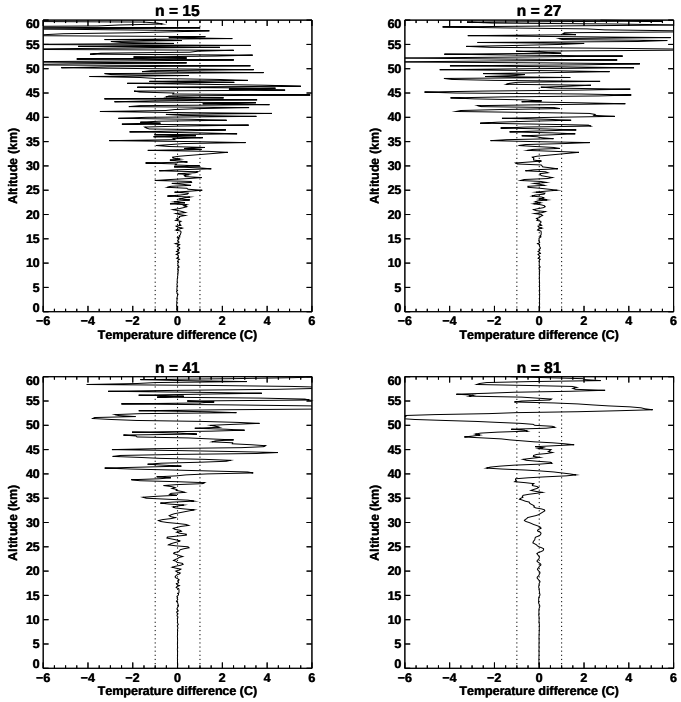

Fig. 2: Temperature deviations between a retrieval obtained from an arbitrarily selected realisation of random noise with $\sigma_{L1} = 1$ mm and $\sigma_{L2} = 1.2$ mm, and the mean of 1000 noisy retrievals for different excess phase delay filter widths. Deviations of 1 K are indicated by the dotted lines.

1.6 seconds ($n = 81$), significant wave like temperature fluctuations remain. Their amplitude increases with altitude. Depending on filter width, local fluctuations reach 1 K somewhere between 25 and 35 km altitude. Such amplitudes are comparable with gravity wave amplitudes found in radiosonde (e.g., Tsuda et al., 1991, 1994b) or rocket data (e.g., Tsuda et al., 1992).

Standard deviations of the temperature fluctuations related to the simulated noise for three different noise levels (0.5, 1 and 1.5 mm for L1) are shown as function of altitude in Fig. 3. Each figure is based on 1000 realisations of noise. Note that a random ensemble of waves with a certain amplitude will exhibit a standard deviation which is smaller than its amplitude. As a reference, we indicate the range of standard deviations for pure sine waves (calculated over many wavelengths) with amplitudes between 1 and 2.5 K by the gray shaded areas. Thus, if the standard deviation of noise related temperature fluctuations is within the gray region, an individual realisation can be thought of as a

wave–like perturbation with an amplitude between 1 and 2.5 K.

For noise levels typical for GPS/MET (1 mm), standard deviations are below or at most in the order of 1 K below 30 km altitude for all choices of the filter width. Assuming that lower and mid stratospheric gravity waves exhibit amplitudes in the order of 1 to 2 or 3 K (Tsuda et al., 1991, 1992, 1994b), and that planetary scale waves like Kelvin waves may reach amplitudes of 3 to 4 K (Tsuda et al., 1994a), our results suggest that these waves will stand out above the noise in the lower stratosphere. The altitude up to which a 1 K amplitude wave is distinguishable from noise related temperature fluctuations, however, depends on the excess phase filter. For TH02's "optimised" filter, noise related temperature fluctuations enter the range of atmospheric gravity waves at about 30 km altitude. TH02's baseline filter ($n = 41$) may allow to identify 1 K amplitude waves up to 35 km altitude. Between 30 and 40 km, all filter choices cause noise related temperature perturbations with standard deviations of 1 K or more, rendering the detection of small and mid amplitude gravity waves difficult. At altitudes above 40 km, the standard deviation exceeds 2 K for all but the strongest excess phase filtering; any interpretation of temperature fluctuations as atmospheric gravity waves is probably misleading. This is consistent with the findings of TH02, who also discarded temperature data above this altitude.

The altitude range which allows the detection of small amplitude gravity waves, as judged from the altitude where noise related standard deviation is below that of a 1 K sine wave, also depends on the noise level of the observations. For TH02's optimised filter, the upper limit varies between 25 km (for 1.5 mm L1 noise) and 33 km (0.5 mm L1 noise) altitude; or between 33 and 40 km for their baseline filter.

We further note that, at least for short filter widths and high noise levels, the effects of the statistical optimisation become apparent. For the $n = 15$ filter, a step–like change in the standard deviations appears around 30 km, where the statistical optimisation sets in. Also note that the statistical optimisation affects higher noise levels stronger than lower noise levels at altitudes above 40 km. This is related to the fact that the heuristic noise filter described by Hocke (1997) is not based on optimal estimation principles; see

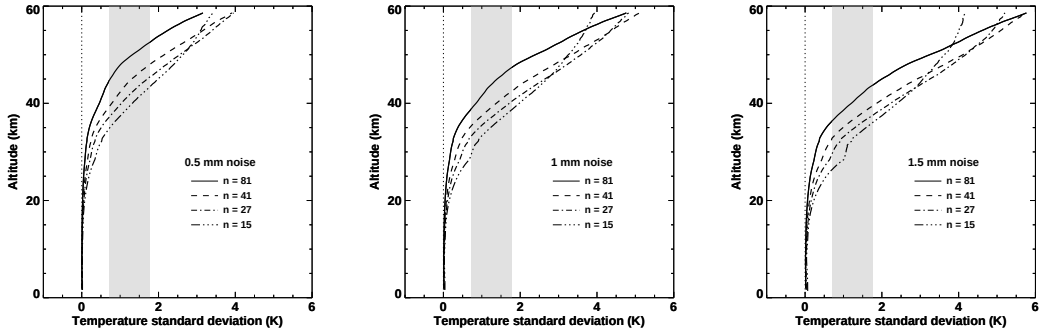

Fig. 3: Standard deviations of temperature fluctuations for L1 excess phase delay noise standard deviations of 0.5, 1 and 1.5 mm (from left to right). L2 noise levels have been assumed to be 20% larger than for L1. The gray shaded areas denote standard deviations for plain sine waves with amplitudes between 1 and 2.5 K.

Healy (2001b) for details.

Gravity wave parameters are calculated from residuals of the original temperature profile against an undisturbed background temperature. A polynomial fit to the full temperature profile over a certain altitude range is often used for this purpose (e.g., Allen and Vincent, 1995). Here, we follow the alternative approach by Tsuda et al. (1991, 2000), where the gravity wave signal is obtained by high pass filtering the original temperature profile, only retaining temperature variations with vertical wavelengths below 10 km. AS in TH02, we calculate vertical wave number spectra of the normalised temperature fluctuations (see, e.g., Tsuda et al., 1991, 2000; Allen and Vincent, 1995, for details). Again, we emphasise that the original temperature profile used in our simulation does not contain any temperature fluctuations related to gravity (or other small scale) waves; any vertical wave number spectra obtained in this analysis therefore reflect noise.

Fig. 4 shows vertical wave number spectra for noise ranging from 0.5 to 1.5 mm (for L1), the same filter widths as applied before, and for the altitude ranges 20–30 km and 30–40 km, respectively. All spectra represent averages over 1000 realisations of noise. We note that typical maxima in power spectra obtained from, e.g., radio sonde data vary between 0.01 and 0.1 m / cycle at characteristic vertical wavelengths around 5 km (see, e.g., Smith et al., 1987; Allen and Vincent, 1995; Tsuda et al., 1991). Thus, at 20–30 km altitude, the contribution of noise to the power spectral density is by two orders of

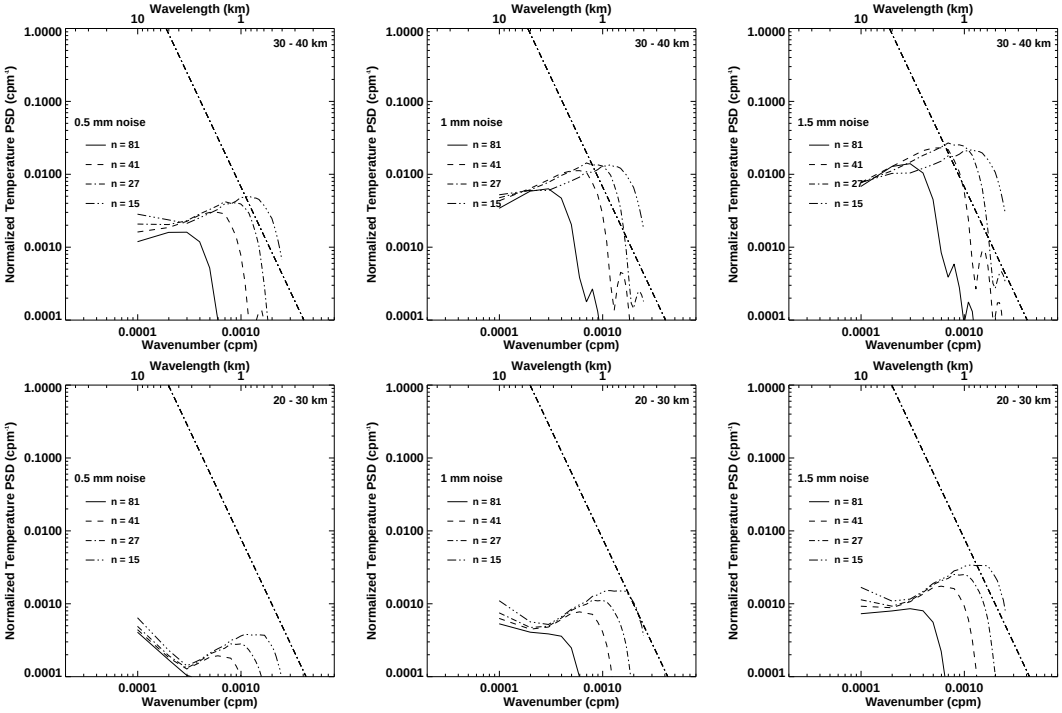

Fig. 4: Vertical wavenumber spectra calculated from an ensemble of simulations in the altitude ranges of 30 – 40 km (top) as well as 20–30 km (bottom), respectively. Shown are power spectral densities (PSD) as function of vertical wavenumber for simulated excess phase delays with standard deviations of σ_{L1} = 0.5 mm, σ_{L1} = 1 mm, and σ_{L1} = 1.5 mm (from left to right). Noise added to the simulated L2 phase delays have been increased by 20% compared to L1. The dashed diagonal line indicates the saturation limit of internal gravity waves as given by Smith et al. (1987) for reference.

magnitude smaller for vertical wavelengths above 2 km. Atmospheric waves with vertical wavelengths above 2 km will be above the noise level, and dry temperature retrievals are well suited for the analysis of such temperature perturbations.

However, we also find that the excess phase delay filtering has a profound impact for vertical wavelengths at and below 2 km. For an L1 noise of 1 mm, i.e. a noise level typical for GPS/MET data, the TH02 optimised filter (n = 15) generates a “gravity wave energy” for vertical scales below 1 km which matches the theoretical saturation limit. We note that the spectral shape of the noise related temperature fluctuations for small vertical wavelengths is similar to the saturation spectrum expected for gravity waves. Clearly, the contribution of noise to energy contained in scales below 2 km also depends on the noise level: For 0.5 mm L1 noise, atmospheric gravity waves with wavelengths below 2 km are above the noise’s signal. For noise levels of 1 or 1.5 mm, atmospheric gravity

waves with vertical wavelengths below 1 km will be masked by the noise when filter settings as in TH02 are used. We conclude that the heuristic tuning procedure applied by TH02 is not suited to optimise the vertical resolution of dry temperature retrievals, because the increase of energy at small vertical scales might partially or entirely be related to measurement noise. In general, the ability to interprete vertical wave number spectra obtained from radio occultation dry temperature data for wavelengths below 2 km depends on the noise level and the filter settings – even in the 20–30 km altitude range.

In the 30–40 km region, the effects of noise are by an order of magnitude larger than in the altitude range below. Here, even the baseline smoothing of TH02 (n = 41 in our setup) provides a wave number spectrum which is close to saturation for wavelengths at and below 2 km, regardless of the noise level. While large amplitude waves with vertical wavelengths above 2 or 3 km may still provide gravity wave energies above the noise level, we conclude that no interpretation of dry temperature data for wavelengths below 2 or 3 km is possible in this altitude region. Again, the spectral shape of the noise is similar to the one expected for saturated gravity waves. We note that the energy contained in our simulated noise data for short wavelengths is larger than that obtained by TH02 from GPS/MET data in the same altitude range. As this region is affected by details of the statistical optimisation, we believe that the most likely explanation are differences in its implementation. These discrepancies also highlight the sensitivity of gravity wave parameters calculated from radio occultation data to technical details in the retrieval, and especially the treatment of noise. They stress the necessity to take noise characteristics of the raw data, as well as details of the filtering and smoothing procedures applied during the retrieval, into account when analysing radio occultation data in the context of atmospheric small scale waves.

Because the contribution of noise to the calculated potential energy for vertical wavelengths below 2 km is large even in the altitude range 20–30 km, its contribution to the meridional variability of gravity wave energy (as discussed in TH02) might also be an issue. Fig. 5 shows an estimate of the mean noise and its standard deviation ob-

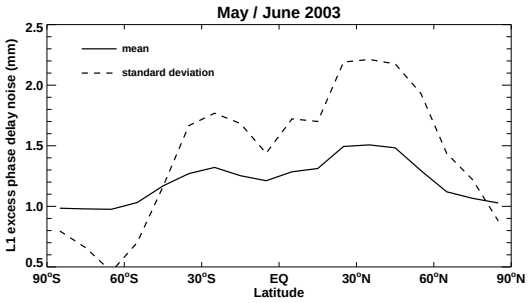

Fig. 5: Mean noise of L1 excess phase delays estimated from about 4500 CHAMP measurements obtained between 14 May and 10 June, 2003 (solid line), sampled in 10° wide latitude bins. The dashed line denotes an estimate of the standard deviation of the L1 phase noise for the same period.

tained from 4552 L1 excess phase delay profiles collected by CHAMP between mid of May and mid of June 2003. Our estimate is based on fitting a smoothing spline to the initial 1000 data points (i.e., during the first 20 seconds) of each individual occultation. During this period, the atmospheric contribution to the measured signal is weak, and therefore allows an estimate of the noise component. We apply a Generalised Cross Validation (GCV) algorithm (Wahba, 1975; Craven and Wahba, 1979) to objectively determine the smoothing parameter; the method also provides an estimate of the residual noise. Tests applying the method to our simulated data set have shown that the GCV provides excellent estimates of the noise for all noise levels considered in this note.

The zonal mean excess phase delay noise distribution shown in Fig. 5 indicates some meridional variability with maximum noise levels (up to 1.5 mm) in the subtropical regions of both hemispheres. In the tropics, the noise level is also increased (1.2 mm) compared to the extratropics (1 mm). The large variability of the standard deviation of the estimated noise suggests that the noise in raw radio occultation data is subject to significant spatial variability, although a detailed discussion of the noise properties is beyond the scope of this note. Similar to TH02, we have calculated potential "gravity wave" energies E_p related to noise induced temperature fluctuations with vertical wavelengths below 2 km by integrating the wave number spectra numerically. For the TH02 filter settings and in the 20–30 km altitude range, we obtain potential energies of 0.21 and 0.46 J/kg for noise levels of 1 and 1.5 mm, respectively. Taking the meridional variation of the Brunt–Vaisala frequency into account, the range of possible potential energy

densities associated with noise can be expected to vary between 0.2 and 0.54 J/kg. These numbers are comparable with the range of meridional and seasonal variability estimated in TH02 (exhibiting absolute values between 0.3 and 1.4 J/kg, according to their table 2; meridional variations are in the order of 0.5 J/kg). Similar geographical variations in the characteristics of noise as in CHAMP data may or may not have been present in GPS/MET data used by TH02. However, conclusions on the meridional distribution of gravity wave energies for wave lengths below 2 km may certainly only be drawn if the noise level and its spatial characteristics are considered appropriately.

3 Discussion

By adding realistic levels of uncorrelated Gaussian noise to simulated excess phase delay data, we have found that small vertical scale fluctuations in dry temperature radio occultation data can safely be interpreted in terms of gravity or other small vertical scale waves in the altitude region of 20–30 km, and for vertical wavelengths above 2 km. The details of the altitude and wavelength region depend on both the noise levels of the observations and the filtering applied during the retrieval. We note that the noise levels applied in our simulation are consistent with independent estimates of the noise present in GPS/MET data, and are likely to represent a reasonable estimate for CHAMP data as well.

It should be kept in mind, however, that noise related dry temperature perturbations exhibit irregular, but wave–like characteristics; their vertical “wavelength” is determined by the filtering. The interpretation of radio occultation dry temperature data outside of the safe altitude and wavelength windows described above requires that the actual noise level of the observations as well as the filter procedures applied to them are taken into account.

For vertical wavelengths below 2 km, dry temperature fluctuations may generally be related to noise, even at altitudes below 30 km. “Optimising” the excess phase delay filtering for this region of the atmospheric wave spectrum, as in TH02, may raise noise related fluctuations to levels comparable to saturated gravity waves. The interpretation

is complicated by the fact that the spectral shape of noise for wavelengths below 2 km is similar to the one expected from saturation theory. In the altitude range between 30 and 40 km, realistic noise levels prohibit the interpretation of dry temperature fluctuations with less than 2 km vertical wavelength. Large amplitude gravity waves with wavelengths above 2 km may or may not stand out above the noise in this altitude range, depending on noise and filter characteristics.

Meridional variations in integrated (over short vertical wavelengths below 2 km) zonal mean potential energy of gravity waves, as discussed in TH02, may be influenced by spatial (and possibly temporal) variations in the noise of radio occultation data. The reason for the variability found in, e.g., CHAMP data is currently unknown. However, noise related temperature fluctuations provide integrated potential energies comparable to real atmospheric waves even in the 20–30 km altitude range. Therefore, conclusions on the spatial distribution of potential gravity wave energies for vertical wavelengths below 2 km, as discussed in TH02, can only be drawn from dry temperature radio occultation data when spatial characteristics of the observational noise are also considered. Depending on the actual noise level of the data, such conclusions may not be possible at all.

The use of the “statistical optimisation” has not been addressed in this comment. However, it causes further complications: The amount of smoothing introduced by the statistical optimisation depends on an estimate of the noise in retrieved bending angles (which depends on the noise in excess phase delays). The filter characteristics therefore vary according to the spatial and temporal variation of the noise. In TH02 as well as in this study, the statistical optimisation is limited to altitude regions above 30 km. Thus, our conclusions for the 20–30 km altitude range are not affected. However, the interpretation of vertical wave number spectra in altitude ranges above will be even more complicated.

As a general consequence, the vertical resolution of radio occultation data is in practice limited by the level of noise and the amount of filtering applied to the raw data, rather than the theoretical physical limitations of the method (e.g., the Fresnel diameter in case of phase based retrievals). More advanced retrieval methods also use amplitude

data, and usually claim significantly higher resolutions than the traditional retrieval. We believe that our conclusions are valid for these methods as well: Noise in the phase data will cause similar problems for these algorithms. Additional complications arise from uncertainties in the measured amplitudes, which are considered to be less precise than phase measurements.

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